RATIONALE FOR THE DEVELOPMENT OF THE FULL-TIME GRADUATE PROGRAMME IN FLUID CONTROL SYSTEMS AND ELEMENTS

I. INTRODUCTION

Fluid Control Systems and Elements deal with engineering applications such as pneumatic and hydraulic controls and hydraulic power systems where fluid motion and displacement contain and transmit information as well as power. Fluidics, a sub-area restricted to devices containing no moving mechanical parts such as fluid jet amplifiers and logic elements, has gained prominence since 1960. Few universities offer advanced programmes in Fluid Controls, in spite of the fact that the largest number of industrial controls are either hydraulic or pneumatic systems. The process industry, faced with new developments such as Fluidics and Computer Control need engineers with the highest qualifications in Fluid Controls to solve the specialized problems unique to their applications. Graduate studies in the area are broadly based on subjects such as Fluid Mechanics, Control Theory, Simulation and Physical Systems which form a major part of the existing graduate programme at SGWU. In the Faculty of Engineering, considerable interest exists for research in Fluid Controls, especially in Fluidics. Early in 1967, the Faculty of Engineering committed resources to the development of the Fluid Controls area and this group has gained the continuing encouragement and support of NRC and industry. A Doctoral programme in Fluid Controls started in 1968, but its development has been hampered by a BGS decision which has the effect of allowing only two Doctoral students in the area.

II. BACKGROUND ON THE DEVELOPMENT OF FLUIDICS

Since 1960, interest in Fluidics has expanded continuously and in 1967 it was estimated that over one hundred research agencies and universities in the United States were conducting research in this field, with an estimated annual expenditure of $30 million.

Interest in Europe, particularly in the United Kingdom, has become very keen during the last five years; three Fluidics

Conferences have been held at Cranfield, England (the Fourth Cranfield Conference will be held in March, 1970 at which Dr. Kwok of our Fluidics Research Group will be presenting a paper).

Russia first demonstrated fluidic amplifiers in 1960 but it is not clear to what extent they have expanded their research activities since then.

The importance of Fluidics as a research and development area has been recognized by the Professional Engineering Societies, as evidenced by the fact that the American Society of Mechanical Engineers formed a separate Fluidics Committee in 1966 under the chairmanship of Dr. F.T. Brown of M.I.T.

In Canada, the initiative has been taken essentially by only two universities (SGWU and Saskatchewan), and NRC and the Montreal-based Aviation Electric Ltd. A separate Fluidics Section was formed at NRC early in 1967. Later that year, the NRC Associate Committee on Aerodynamics established a Research Co-ordination Group on Fluidics under the Chairmanship of Mr. W. Hayes, to recommend on areas of research in Canada for fluidic components and systems. Their report is discussed further in Section IV.

At SGWU the research area of Fluid Controls has been developed in the Faculty of Engineering over the last 2 1/2 to 3 years. The considerable interest for research in this area was first outlined in the report to Dr. J.M. Roxburgh of NRC (December 1967). A full-time graduate programme started in 1968 and the Doctoral proposal dated April 19, 1968 delineated the reasons for choosing this area. It identified the faculty members with teaching and research experience in the area and it also summarized the commitments made by the Faculty of Engineering to the development of fluid controls.

III. DEVELOPMENTS TO DATE

The fluid controls programme is being developed according

to the research policy of the Faculty of Engineering. This policy is to concentrate support in a few well defined areas involving research team effort, primarily on projects related to industrial problems and which preferably complement local research and development programmes.

Development of the area has progressed in the following ways:

1. The number of faculty members interested in doing research in fluidics has increased from four to seven. Appendix A identifies the faculty members and the research associates and research assistants in the Fluidics Research Group. A recent addition to our faculty is Dr. Clyde Kwok who has made a major contribution to the development of fluidics. Mr. Henri Azria, a coopérant militaire from the University of Paris, is completing his 14 months of compulsory military service as a research assistant in the group. The group has therefore gained considerable strength and it will continue to attract researchers of the highest calibre.

2. A graduate course in Fluidics, probably the first of its kind in Canada, was given for the first time to approximately 25 graduate students. Several guest lecturers participated and the course was well received by industry in general and the students in particular. The contents, shown in Appendix B, will be modified based on experience gained and it will be offered again next year.

3. A number of research projects has been defined (see Appendix C) and distributed to students wishing to undertake research theses. To date, 13 Masters and two Doctoral students have undertaken projects in the area, thus adding considerable impetus to the research group.

   On October 3, 1969, one of the Doctoral students, S. Lequoc, successfully completed his General Doctoral Examination and we are happy to report that he has now joined the Université de Quebec as an Assistant Professor of Engineering in the Faculty of Applied Science at Chicoutimi. The Université de

Quebec wishes Mr. Lequoc to complete his Doctorate of Engineering at SGWU and they have agreed to arrange his teaching schedule so that he can continue with the programme starting next summer. The second Doctoral student, Mr. Farag, has changed from a Ph.D. programme at McGill to the programme at SGWU after discussions with various members of the research group and a detailed examination of our research projects and facilities. Dr. Kwok will be his research director. The research programme is thus attracting high quality students and although none has yet graduated, our programme is gaining rapid recognition and there is every indication that our graduates will be well received in industry and the universities. A third well qualified Doctoral applicant was turned down by the BGS because of the arbitrary restriction which limits to a total of six the number of Doctoral students permitted in the three research areas in the Faculty of Engineering.

4. A close liaison has been maintained with the newly formed Fluidics Group in the NRC Control Systems Laboratory. The Doctoral proposal of April 19, 1968 noted that they had agreed to build special research components for us and they invited our research team members to participate in special projects in these laboratories. Last summer one of our research associates spent several weeks working with the NRC group on such a project. In June 1969, NRC sponsored a meeting of Fluid Research organizations at SGWU to discuss and coordinate the different research projects being carried out in Canada. The meeting was attended by the 30 leading researchers from industry and universities in Canada.

   There has been a growing interest to formalize the liaison with the NRC research group so that NRC personnel could work on a regular basis directly with faculty members and graduate students on projects of mutual interest. Discussions with NRC over the last month have resulted in the offer of an appointment to Mr. William Hayes, Associate Research Officer, as NRC Adjunct Professor in the Mechanical Engineering Department (see letter from J. Bordan to Dr. McPhail, and from Dr. Tanner to M.P. du

Plessis, Appendix D).

5. The close liaison maintained with industry, especially with the Montreal-based Aviation Electric Ltd. has resulted in their seeking additional financial support for our research programme. Mr. E. Wall, Vice-President of the company, has sought ways in which our programme could be aided by them through the Industrial Research Assistance Programme and through supplemental NRC Industrial Research Grants. In a very recent letter, dated October 6, from Mr. Wall, he states that as a first step, Aviation Electric has decided to contribute $5000 to our programme, preferably to be used to finance a full-time Doctoral student in Fluidics (see Appendix E, letter from Mr. E. Wall to M.P. du Plessis). They have also agreed to participate in our negotiations with NRC for support of our programme over a three- to five-year period.

   Industry in general is becoming aware of our activities in Fluid Controls as evidenced by the fact that an Industrial Fluid and Pneumatic Logic Symposium was held at SGWU on September 3-5, 1969, and was sponsored jointly by the Instrument Society of America and the Fluid Power Society. It was attended by 180 engineers from industry and universities throughout Canada.

6. The Fluidics Research Group has systematically reported their work in the form of Internal Research Reports (see Appendix F for listing). The reports are circulated throughout the Faculty of Engineering and two copies are deposited at the Science and Engineering Library for the use of Graduate students and other researchers. Where work has progressed to a suitable point, the reports form the basis for publication in technical journals. This first such paper(1) was accepted for presentation at the ASME Conference in Chicago on June 16-18, 1969. It describes a Fluidic Signal Generator developed, built and tested in our research laboratories. The SGWU unit has a linear response over a frequency range far exceeding that of units available commercially or built in other research laboratories to date. It

therefore has commercial potential and a patent application was made on 25 July, 1968 (see Appendix G). Researchers at the University of Waterloo have expressed interest in a newer version of the signal generator and have since placed an order for one of these units from us.

7. Financial Support

Appendix Table I shows the financial support received for the Fluidics Group since its inception in 1967. It shows that the total support received has risen from approximately $10,000 in 1967/68 to approximately $37,000 in 1969/70. At present, about $9,000 is available for the support of two more Doctoral students, or for partial support of three Doctoral students, but our number is limited by the arbitrary number of six for the three research areas. It is therefore apparent that the group has been able to receive the necessary support for a number of students larger than that permitted at present.

IV. THE ROLE OF SGWU IN FLUIDICS RESEARCH

The NRC Fluidics Sub-Committee of the Associate Committee on Aerodynamics, in November 1967, recommended areas of fluidics research which are summarized in Appendix Table II.

It also listed the institutions conducting research in areas related to fluidics as follows: Laval, McGill, SGWU, Waterloo and Saskatchewan, NRC and Aviation Electric Ltd.

Whereas most of the universities listed are conducting work in fluid dynamics related to fluidics, only SGWU and Saskatchewan emphasize research on Devices and Systems. Fluidics has not been applied more generally in Canadian industry because of the lack of systems and devices that are compatible with existing electric, pneumatic and hydraulic controls and some

universities should concentrate on this area to solve these problems and also to provide industry with the specialized personnel for their development programmes. Dr. Kwok, with his outstanding experience in this area, is ideally suited to undertake this task. There is therefore already a nucleus at S.G.W.U., and industry and other institutions will look more toward this group for the necessary guidance and assistance.

V. FACTORS DETERMINING THE SIZE OF THE GRADUATE PROGRAMME

In order to establish the level of the full-time graduate programme, it is necessary to consider the following:

a) The requirements of industry, government and universities for engineers with the highest engineering qualifications.
b) The number of graduate students that can be accommodated in our research laboratories to ensure optimal use of the facilities.
c) The need to provide faculty members teaching graduate courses with the necessary number of full-time graduate students.
d) The financial support that can be expected for full-time graduate students.

Since each of the above considerations will produce a different number, the final size of the graduate programme will inevitably be a compromise between these four requirements:

(a) The NRC Forecasting Committee(2) reports that the production rate of Engineering and Science Doctorates in Canada has been sufficient to supply only the expansion needs for new university faculty without satisfying the needs of industry. It also points out that if the university faculty growth rate remains at 13% per year, Canada will continue to have an overall deficit of Engineering and Science Doctorates. It is reasonable to assume therefore that the production of engineers with the highest academic qualifications will remain below the industrial demand for several years, especially if the overall industrial requirements increase at the predicted rate of 10 to 20%.

In order to establish the number of full-time graduate students, it is necessary to identify some of the industries concerned and estimate their requirements for graduates with the highest engineering qualifications.

The NRC Fluidics Sub-Committee of the Associate Committee on Aerodynamics in November 1967 recommended that support for fluidic research should be particularly encouraged where it will assist in the exploitation of distinct Canadian capabilities and resources. In particular the following industrial application areas were suggested:

Process industry applications
Pulp and paper industrial controls
Medical applications
Nuclear power controls
Agricultural equipment controls
Aerospace applications
- VTOL and STOL autopilot systems
- VTOL, STOL and helicopter stabilization
- VTOL, STOL airspeed and air data systems
- Small gas turbine control systems
- Aircraft cabin control systems
- Aircraft cabin environmental control

and some military applications.

To this list should be added many secondary manufacturing industries who turn out products having a high technological content. These companies have the highest potential growth rates and they will be encouraged to invest more heavily in R and D if an adequate number of highly qualified Engineering Doctorates are available. Other industries wishing to incorporate fluidics or direct digital control in new plant expansions or wanting to adapt existing pneumatic or hydraulic control systems to these new control techniques, will increase their demand for Engineering Doctorates.

An estimate based on the approximate number of companies in Canada in the above categories indicates the immediate need for a national annual output of between 25 and 40 Doctorates and between 40 and 60 Masters graduates in Fluid Controls.

The requirement for Doctorates in universities and government is further estimated at between 5 and 10 per year. The total national annual requirements may therefore be between 30 to 50

Doctorates and between 60 to 80 Masters graduates in Fluid Controls. Since only one other university has a graduate programme in this area about half of these numbers should be provided by SGWU, i.e., 15 to 25 Doctorates and 30 to 40 Masters graduates annually.

(b) The optimum use of research laboratories (see Appendix Table III), equipment and personnel can only be ensured by the presence of an adequate number of full-time graduate students. Appendix Table IV summarizes the research topics and the number of students that should be associated with each project to ensure the best utilization of our resources. It indicates that a total of 27 M.Eng. and 13 Doctoral students can be accommodated in the existing laboratory space (9,000 sq.ft.) plus the 1100 sq.ft. requested for Fluid Controls in 1970/71. In addition, it is possible for 22 M.Eng. students to undertake theoretical dissertation work associated with some of these topics. The number and types of M.Eng. dissertations and D.Eng. theses associated with each research topic depend on the nature of the topic and the experimental facilities available. For instance, Doctoral theses can only be undertaken in 8 of the 15 research topics and the largest number of Doctoral students can be accommodated in two of the areas (Turbulence-Noise and Vortex Rate Sensor) where the topic lends itself to extensive theoretical as well as experimental analysis. Other topics such as the signal generator can best be investigated at this stage as an experimental M.Eng. dissertation.

(c) It is generally accepted within SGWU that a typical Faculty work load consists of approximately ten contact hours per week. Where Faculty members teach graduate courses a common assignment consists of six lecture contact hours per week plus four contact hours per week assigned to graduate student supervision and personal research. It is of the utmost importance that this latter capability within the university be utilized to the fullest extent.

Full utilization of the Faculty resources in the Fluid Controls area can be achieved as shown in Appendix Table V. The total

numbers of 26 M.Eng. and 8 D.Eng. students are based on average teaching loads and the average times required for supervision of M.Eng. and D.Eng. students during their two to three year programmes.

(d) Financial Support

The projected financial support over a three-year period is based on the past pattern of support from NRC and an anticipated increase in the support from industry. The breakdown of funds for support of Research Assistants, Associates and Doctoral students is also shown in Appendix Table VI. It indicates that support can be built up for two Research Associates, ten Research Assistants, and 14 Doctoral students over a three-year period. It also indicates that funds are available this year to support two to three Doctoral students.

CONCLUSION

The choice of the size of the graduate programme lies somewhere between the constraints of (a) to (d), Section V. The most pessimistic of these is the estimate of the financial support, although this could increase drastically depending on the productivity of the group and the rate at which smaller secondary industry decides to support our programme.

The following plan for development of Doctoral studies would appear a reasonable compromise to work towards satisfying the requirements of industry, faculty, the need for optimum use of our research facilities and for which financial support can be expected:

1. Set as objectives the following number of Doctoral students in the programme; 5 in 69/70, 8 in 70/71, 12 in 71/72, 16 in 72/73.
2. The actual number of students admitted each year should be determined by the availability of suitably qualified students, financial support and within the general constraint of average faculty work loads of ten contact hours per week.

REFERENCES

1. A Pressure Signal Generator for Fluidic Research, J.C. Vrana, N. Suresh, M.P. du Plessis and J.C. Callaghan, ASME 69-FLCS-40, June, 1969.

2. Projections of Manpower Resources and Research Funds 1968-72, Report of the Forecasting Cmte National Research Council of Canada, February 1969.

M.P. du Plessis

20 October, 1969

Financial Support of Fluidics Research Group

Researcher	1967/68 NRC	1967/68 Other[1]	1968/69 NRC	1968/69 Other[1]	1969/70 NRC	1969/70 Other[1]
J.C. Callaghan	$3000		$7350	$2000	$8000	$800
M.P. du Plessis	$4600	$2000	$5340	$7570	$5000	$2000
W.M. Mansour	NA		$2940		$3000	
G.K. Fleming	NA		$2950		$3600	
M.O.M. Osman	NA		$500[2]		$1000[2]	$600
T.S. Sankar	NA		NA		$2000[2]	
C. Kwok	NA		NA		$3000[3]	
G.S. Mueller	NA		NA		$3000[3]	
AEL					$5000	
Sub-total	$7600		$19,080	$9570	$33,600	$3400
TOTAL			$28,650		$37,000	

(1) CASA

(2) Partial support of fluidics research

(3) Anticipated amount from interim request.

APPENDIX TABLE II

AREAS OF FLUIDIC RESEARCH

BASIC RESEARCH

Fluid Dynamics

- jet interactions in complex geometries
- transmission line phenomena and theory
- noise generation, measurement and suppression
- multiphase flows
- instrumentation and visualization techniques
- flow in complex geometries

Devices

- amplifiers (digital and analogue)
- passive devices
- transducers (input and output)
- computation components
- hybrid devices
- multiphase devices

Systems

- device and transmission line transfer function
- information processing systems
- development of system analysis techniques

APPLIED RESEARCH

- device miniaturization
- contamination
- fabrication techniques
- power supplies
- input/output devices and peripheral hardware

Laboratory Space

Room No.	Description	Dimensions	Area
H0027	General Mechanical Engineering Laboratory	65' x 46'	3000
	Mezzanine 1	21'9" x 46'	1000
	Mezzanine 2	21'9" x 46'	1000
H0027	Engine Laboratory	21'9" x 46'	1000
H0026	Fluidics Research Laboratory	30' x 20'	600
H0021	Hydraulics Laboratory	60' x 30'	1800
	Mezzanine	20' x 30'	600
		TOTAL	9000

Number of students required to optimize use of laboratories

Research Topics	Number of M.Eng. Dissertations		No. of D.Eng. Theses
	A	B	A
Turbulence-Noise Studies	4	4	3
Transmission Line Studies	3	3	2
Transducer Studies			
Signal Generator	2	-	-
Angular Rate Sensor	1	1	-
Liquid Level Sensor	1	-	-
Vortex Rate Sensor	4	4	3
Hybrid Fluidic Devices			
Free Disc Devices	1	-	-
Magnetic Disc Devices	1	1	-
Machine Tool Control*	2	1	1
Three-Mode Fluidic Process Controller*	2	2	1
Jet Engine Control*	1	1	1
Paper Machine Control	2	2	1
Turbulence Amplifiers*	2	2	1
Fluid Resistors*	1	1	-
TOTALS	27	22	13

*Projects in conjunction with NRC

(a) A - Requires experimental laboratory facilities

B - Primarily theoretical in nature. Do not require experimental facilities.

APPENDIX TABLE V

Faculty resources for graduate student supervision

Faculty member		M.Eng.	D. Eng.
Callaghan		1	-
du Plessis		4	2
Fleming		4	1
Kwok*) Hayes)		8	2
Mueller		4	1
Osman		4	1
Sankar		2	1
	TOTALS	26	8

APPENDIX TABLE VI

Projected Income and Distribution of Funds

Source	Present 1969/70	1970/71	1971/72	1972/73
NRC	$33,600	$40,000	$57,000	$70,000
CASA	3,400	2,000	1,000	1,000
Industry	5,000	10,000	17,000	25,000
TOTAL	$37,000	$52,000	$75,000	$96,000

Distribution	No.	Cost	No.	Cost	No.	Cost	No.	Cost
Res. Associates	2	16,000	2	17,500	2	19,000	2	21,000
Res. Assistants	3	9,000	4	12,000	6	18,000	10	30,000
Doctoral studts.	1	3,000	7	21,000	12	36,000	14	42,000
Other		9,000		1,500		2,000		3,000
TOTAL - $		37,000		52,000		75,000		96,000

FLUIDICS RESEARCH GROUP

Faculty Members

Name	Degree & Year		Field of Specialization
J.C. Callaghan	M.S. M.I.T.	1963	Dynamic Systems, Control, High Frequency Phenomena
M.P. du Plessis	Ph.D. Alberta	1965	Fluid Dynamics
G.K. Fleming	Ph.D. Waterloo	1967	Hydraulic Control Systems, Process Control, Computer Applications
C.K. Kwok	Ph.D. McGill	1967	Fluidics, Fluid Dynamics
G.S. Mueller	Ph.D. Manchester	1969	Gas Turbine Simulation and Control
M.O.M. Osman	D.Ing. Zurich	1965	Machine Tool Design, Digital Controlled Machines, Materials Processing
T.S. Sankar	Ph.D. Waterloo	1967	Continuum Mechanics, Finite Element Methods

NRC Adjunct Professor

W. Hayes	B.Eng McGill (Athlone Fellow)	1955	Controls, Fluidic Systems and Elements

Research Associates and Research Assistants

N. Suresh Research Assoc.	M.S. Nova Scotia	1967	Microwaves, High Frequency Phenomena
R. Kahawita Research Assoc.	B.Sc. Imperial College M.A.Sc. Waterloo	1966 1968	Aerodynamics, Propulsion, Fluid Dynamics
S. Tsang Research Assist.	B.Eng. S.G.W.U.	1968	Fluid Dynamics, Physical Systems
W. Chan Research Assist.	B.Eng. S.G.W.U.	1969	Fluid Dynamics

Name	Degree & Year		Field of Specialization
H. Azria Coopérant Militaire	Diplomé d'Etudes Approfondies - 3e cycle - Paris 1968		Option: Hypersonique et Aérothermique
	D.Eng. Students		
E.A. Farag	M. Eng. Cairo	1969	Fluid Dynamics
S. Lequoc*	M.Sc.A. Sherbrooke	1968	Hybrid Fluidic Heading Reference Using Vortex Rate Sensor
	M.Eng. Students		**Graduate Programme**
I. Thaleshvar	B.Sc.(Eng.) London U.	1966	High speed vortex rate sensor
J. Wong	B.Sc.(Hon.) U. of Strathclyde	1967	Fluidic tape reader
B. Wei	B.S. Ordnance Eng. College Taiwan	1953	Experimental investigation of confined vortex flow phenomena
T. Yoshinaka	B.Sc.(Eng.) Kyoto	1964	Stability in vortex flow phenomena
J. Dagan	B.Sc. Israel Inst. of Technology	1967	Application of fluidics in the field of medicine
N.D. Thinh	B.Eng. U. of Minnesota	1964	Analytical study of confined vortex flow phenomena
R. Schneck	Diploma Zurich Inst. of Technology	1960	Vortex induction pump
H.W. Richter	Hon.Deg. Vienna Polytech.	1956	Fluidic systems
N. Shasha	B.Sc. Diploma Israel Inst. of Technology	1955 1956	Fluidic pulse width modulation system
W. Mak	B.Sc. Chu Hai College Hong Kong	1964	Laminar flow in fluidic resistors
I. Wierba	B.Eng. McGill	1964	Flow through bends

*Non-resident student. At present Assistant Professor of Engineering, Université de Québec.

SIR GEORGE WILLIAMS UNIVERSITY

Faculty of Engineering

Course Outline - Fluidics E651

Lecture No.	Date	Lecturer	Outline
1	29 April	M.P. du Plessis	Basic concepts, flow variables, non-dimensional numbers, similitude, compressible, incompressible, laminar and turbulent flow. Experimental relations for pipe flow: friction factor, Reynolds number, velocity profiles, laminar and turbulent boundary layers.
2	1 May	ditto	Basic and subsidiary laws: conservation of mass, momentum and energy. Stokes hypothesis and the Navier-Stokes equations for laminar and turbulent flow, two-dimensional boundary layer equations.
3	6 May	ditto	Energy equation and one-dimensional compressible flow, unsteady, frictionless, compressible flow.
4	8 May	ditto	Fluid system elements: resistance, capacitance, inductance, inertance, survey of fluidic and hybrid devices.
5	13 May	ditto	Fluid dynamics of free jets: characteristics and basic equation for laminar and turbulent, two-dimensional axially symmetric jets, stability of jets.
6	15 May	ditto	Fluid dynamics of attached jets: theoretical analysis of attachment process.
7	20 May	ditto	Beam deflection proportional amplifiers: performance criteria, gain analysis, transfer characteristics, efficiency and power output.
8	22 May	*C. Kwok and A. Keates*	Wall attachment devices: operation, gain, switching. Example of an industrial approach in development of a bistable device.

Lecture No.	Date	Lecturer	Outline
9	27 May	C. Kwok and A. Keates	Elements of vortex motion and vortex devices, static and dynamic characteristics of the vortex rate sensor.
10	29 May	J.C. Callaghan and N. Suresh	System analysis, resistors in parallel and series, frequency characteristics, R-C circuits, operational amplifiers.
11	3 June	ditto	Fluid circuit theory, transmission line equations, application to lumped circuits, transmission line modelling and matching.
12	5 June	L. Kelly**	AC fluidics: basic principles of carrier systems (general), possibility and advantages of using such systems in fluidics, frequency and other limitations, some typical operational systems, obstacles to further increase in operating frequencies and future trends.
13	10 June	W. Hayes***	Manufacturing techniques for fluidic devices.
14	12 June	C. Kwok and A. Keates	Design of fluidic and hybrid systems; examples of industrial applications.
15	17 June	S. Lequoc	Characteristic curves and staging, source and load characteristics, characteristic curves for proportional and bistable devices.
16	19 June		FINAL EXAMINATION

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†1. Kirshner, J.M. (Ed.) FLUID AMPLIFIERS, McGraw-Hill Book Co., N.Y. 1966.

2. Schlichting, H., BOUNDARY LAYER THEORY, McGraw-Hill Book Co., N.Y. 1968 (6th edition).

†3. Lethan, D.L., FLUIDIC SYSTEM DESIGN (reprinted from MACHINE DESIGN), Vol.1-3 (1966); Vol. 4 (1967); Wood, O. Lew, DESIGN GUIDE PURE FLUID DEVICES (reprinted from MACHINE DESIGN) June 24, 1965.

4. Pai, S.-I., FLUID DYNAMICS OF JETS, D. Van Nostrand Co. Inc., N.Y. 1954.

5. Selected Papers.

* Aviation Electric Ltd., Montreal.
** General Electric, Research and Development Co., Schenectady, N.Y.
*** Control Systems Laboratory, National Research Council of Canada, Ottawa.

† Available at S.G.W.U. bookstore.

APPENDIX C

TOPICS FOR GRADUATE RESEARCH STUDIES IN FLUID DYNAMICS AND SYSTEMS RELATED TO FLUID AMPLIFIER TECHNOLOGY

Mechanical Engineering Department

August 1969

(For internal use only)

I. FLUID DYNAMICS OF FLUIDICS

- TURBULENCE-NOISE STUDIES
- ANALYTICAL AND EXPERIMENTAL INVESTIGATIONS OF CONFINED VORTEX FLOW PHENOMENON
- FLUID VORTEX RATE SENSOR
- NEW WALL ATTACHMENT AMPLIFIER DESIGN
- HIGH-SPEED ANGULAR RATE SENSOR
- FLOW THROUGH BENDS
- LINEAR FLUIDIC RESISTORS
- CHARGING AND DISCHARGING PHENOMENA OF FLUIDIC CAPACITORS
- VORTEX INDUCTION PUMP
- LAMINAR JET PROPORTIONAL AMPLIFIER
- TURBULENCE AMPLIFIER CAVITY OPTIMIZATION
- LAMINAR JET STUDIES

TURBULENCE NOISE STUDIES

The research into this area is aimed towards characterization of turbulence-noise in proportional fluid amplifiers. It is considered that a characterization of jet turbulence in terms of its frequency composition and as a function of the operating jet parameters and measurement location would be of great value in the design of proportional fluid amplifiers from the point of view of optimizing the signal to noise ratio.

Preliminary investigations have been carried out on the measurement of the power spectra and turbulence component intensities of the turbulence from a 1/2-inch square jet at various locations facing the jet, and as a function of the jet operating parameters. It is proposed to obtain time and space correlations between the components of the turbulence at different points with a view to establishing a better estimate of the distribution of noise frequencies.

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF CONFINED VORTEX FLOW PHENOMENON

A mathematical model* of confined vortex flow has been developed. In an attempt to obtain a closed form solution of the complex Navier Stokes Equations, a constant apparent viscosity was assumed throughout the whole flow field. However, in comparing the experimental measurements with those of the theoretically predicted trends, the apparent viscosity can be seen to vary across the flow chamber. An obvious extension of the theoretical studies would be to consider the variation of the apparent viscosity which may be assumed to be a function of the circulation. The actual trend of the viscosity variation may then be established by careful comparison of theoretical and experimental results.

The earlier analysis was carried out by dividing the whole vortex flow field into two separate regions, namely the outer and inner regions, the boundary conditions at the interface are matched by assuming that the tangential velocity, the tangential shear and the static pressure remain continuous. However, even when all the aforementioned conditions are matched, there exists a discontinuity in the axial velocity distribution. The analytical model will be greatly improved if all the flow parameters can be matched at the boundaries.

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* Thesis by C. Kwok entitled "Vortex Flow in a Thin Cylindrical Chamber and Its Applications in Fluid Amplifier Technology".

FLUID VORTEX RATE SENSOR

The full advantages of a fluidic system can be appreciated only when fluidic sensors, having reliability and operational characteristics compatible with pure fluid logic elements, are developed. One of the more promising concepts in the field of unconventional sensors is the vortex rate type. The overwhelming interest and research efforts devoted so far to this idea result primarily from the fact that the operational principle is extremely simple and the sensor output can be used directly in conjunction with fluid logic elements.

The general configuration of a rate sensor, as shown in Fig. I-1 consists of a thin cylindrical chamber with a porous peripheral wall and a plenum chamber external to the porous wall. There is a centrally located outlet flow orifice which serves as a sink for the flow leaving the vortex chamber. In the absence of chamber rotation about the outlet orifice axis, which is the axis of sensitivity, the chamber flow is radial from the porous wall towards the central orifice. When the sensor is subjected to rotation, fluid coming into the vortex chamber through the porous wall acquires the same tangential velocity as the periphery.

Due to the presence of the sink hole and the effect of conservation of angular momentum of fluid flow, substantial amplification of the tangential velocity is obtained as the flow spirals in towards the centre. The general flow pattern resembles that of the free vortex commonly observed during the draining of

a bathtub.

Angular velocity about the axis of sensitivity is sensed by two small pressure pickup tubes as shown in Fig. I-2. When the vortex chamber is rotating in a certain direction about its sensitive axis, the pitot tube which is directly facing the flow recovers the full dynamic pressure, while the other pitot tube experiences a suction due to flow entrainment. This configuration creates a push-pull effect and resulting differential pressure is generated. The pressure pickoffs interchange their signs as the flow reverses its direction.

The vortex angular rate sensor, using the principle of confined vortex motion provides the means to build no-moving-part devices capable of accurately detecting angular error rate. However, for proper optimization of the geometric confirugations in the rate sensor design, better understanding of the nature of confined vortex motions, in addition to detailed knowledge of the effect of fluid viscosity for the swirling flow within thin cylindrical chambers was required.

One of the most interesting phenomena observed in the development of the vortex rate sensor concerns the low frequency oscillation. It is believed that the generation of low frequency oscillation is caused mainly by the strong radial inflows converging towards the centre and interacting with each other. The transition from the radial into the axial flow must be as smooth as possible in order that the slow oscillation may be minimized. During the recent tests of a series of rate sensors, it was found

that in addition to the low frequency oscillations, there are some very pronounced attachment phenomena. For example, the axial jet leaving the rate sensor had a tendency to latch onto a particular region of the exhaust orifice. Once this happened, the rate sensor failed to respond to any rate input signal. Numerous methods were tried in an attempt to destroy this attachment phenomenon, one of the most successful being the introduction of a central "stabilizing" pin located on the rate sensor axis of symmetry, shown in Fig. I-3a. The pin not only helps to eliminate the attachment, but also acts as an anchor to stabilize the exhaust jet. The stabilizing effect is particularly noticeable under high swirl conditions which produce a central low pressure region and thus cause the flow to latch onto the central stabilizing pin.

However, such a stabilizing pin was found to be very impractical because it was difficult to make and was extremely fragile under shock or other adverse environmental conditions. An alternate modification was made by drilling a hole through the partition plate between the high pressure and vortex chamber as shown in Fig. I-3b. It was found that the central jet not only performs the same function as that of the "stabilizing" pin, but also overcomes the disadvantages offered by the original solid pin configuration.

This very interesting vortex stabilizing phenomenon is found to be very useful; however, the detailed mechanism and various stability criteria are not known. An analytical study of this fluid

dynamic phenomenon would be most useful and the results should have important bearing on the future design of fluidic vortex rate sensors.

NEW WALL ATTACHMENT AMPLIFIER DESIGN

Most of the wall attachment type amplifiers available today are very sensitive to rarefaction wave switching. This undesirable phenomenon usually occurs whenever a bistable amplifier is switched, the compression pulse in the original active leg being followed by a smaller amplitude rarefaction wave which propagates to the control jet of the next element. If the driven bistable element has low stability, then the rarefaction wave may cause false switching to occur (i.e. the pressure pulse switches the next element but the following rarefaction wave sucks it back - hence the driven bistable element does not have memory). It follows that in order for bistable amplifiers to function properly, they must be designed so that substantially higher suction would be required to bring the power stream back, and consequently the amplifier would become less susceptible to rarefaction switching.

Two approaches to the problem were considered. The first method concerns the increase in the amplifier offset. It is believed that if there is insufficient offset between the power nozzle exit and the attachment wall, the rarefaction pulse which generally follows the compressive switching pulse will suck the power jet back to its originally attached side. However, if there is sufficient clearance between the power jet boundary and the wall, the sudden drop in pressure developed by the rarefaction wave would suck the ambient air from downstream of the power jet rather than the jet itself. This idea was tried and

it was found that the improvement in stability and insensitivity to rarefaction wave switching is only marginal.

The alternative method of shifting the position of the control jet farther downstream, as shown in Fig. I-4, is more effective. This modification has a marked stabilizing effect since it allows a strong low pressure bubble region to form between the power jet and the attachment wall. Similar improvement in element stability is noticed when one closed the control jet input on the active side of the bistable amplifier. In addition, the switching mechanism is also changed. The switching of the power jet of a conventional wall attachment bistable amplifier design, where control inputs are located immediately downstream of the power nozzle exit, is caused by momentum interaction in the region adjacent to the nozzles. Although there is no existing theory completely describing the exact switching mechanism, it is generally understood that the control input momentum first deflects the power jet stream, followed by a rapid expansion and eventual destruction of the attachment bubble. The attachment bubble on the control signal side must collapse or rupture before the signal is removed in order to achieve a clean switch. In contrast, the new bistable amplifier design provides control nozzles downstream of the attachment bubble as shown in Fig. I-4.

Switching is executed by a sort of "peeling" action. The jet from the control nozzle, which is immediately downstream of the attachment point, deflects the power jet and causes the

attachment point to move downstream and into the control nozzle region. The shifting of the attachment point immediately causes a build-up of pressure in the attachment bubble region which destroys the attachment phenomenon and switches the main jet stream. The difference in principle of the two fluid dynamics switching processes is verified by the existence of a negative pressure in the control channel of the active side of a conventional device in contrast to a positive pressure in the bistable described.

Advantages of this design are summarized as follows:

(a) The stability of the amplifier is significantly improved because an "unvented" attachment bubble is allowed to be formed. As a result of this improved stability, the performance of the element is less critical of small variations of the geometric parameters.

(b) Because of the increased stability, a bistable amplifier design using this geometric configuration is much less susceptible to "rarefaction-wave-switching".

(c) The control port of the active side of the amplifier has continuous overflow. This particular phenomemon causes the control input impedance to be very high. This high input impedance feature may be utilized so that a large number of similar elements may be switched by the output of a single element (i.e. maximum fan-out capability).

(d) Further modifications (i.e. moving splitter upstream) may be incorporated into such a design so that elements are switched

by simply blocking the active side control port.

(e) As a result of the positive outflow on the active side of the control port, and suction on the inactive side, this special characteristic utilized in conjunction with disc valves, achieves a simple binary counter design as described in a later part of this paper.

This new bistable amplifier is unquestionably better in many respects than the conventional bistable amplifier design; however, the exact geometric configuration is far from being optimized. Moreover, not much is understood regarding the detailed switching mechanism. Any future fundamental research investigation performed along this line will be most useful.

HIGH-SPEED ANGULAR RATE SENSOR

In industrial controls, it is often necessary to detect the speed of a rotating shaft. A simple and very interesting concept on laminar flow impinging on a rotating cylinder may be used. The basic concept is illustrated in Fig. I-5a, which indicates the difference of streamline patterns with and without rotation of the cylinder.

Students may carry out the project by designing a simple speed sensor as indicated in the sketch (Fig. I-5b). A small clearance will be left between the rotating shaft and the casing. For example, when the shaft is rotating in the clockwise direction, most of the fluid flow will probably be carried via the upper passage and there will be very little flow, or possibly even reverse flow occurring in the lower passage. A pressure differential at the output will be generated and its magnitude will be proportional to the speed of rotation.

A mathematical model using viscous fluid flow theory can be developed. The performance of such a device and the interdependence of various flow and geometric parameters should be established.

FLOW THROUGH BENDS

Flow through bends is always an interesting fluid dynamic phenomenon, however, very little work has actually been done in this area. The distortion of fluid velocity profile when passing through bends is of particular interest in the field of fluidics. For example, the centrifugal force field as well as the development of secondary flow in a curved passage produce a distortion of the velocity profile which in turn affects the entrainment phenomena of the jet.

It will be a most interesting, as well as useful project, for some graduate students to carry out an analytical investigation of flow through bends. If possible, to develop some means to minimize the distortion of velocity profiles and pressure losses. The analytical findings may be further substantiated by a series of experimental measurements of velocity profiles in fluid conduits of rectangular as well as axisymmetric cross-sections.

LINEAR FLUIDIC RESISTORS

Fluidic resistors generally consist of capillary tubes or orifices. The orifice type has a highly nonlinear pressure flow characteristic while the capillary type provides remarkably linear pressure-flow relationship because it uses the frictional or viscous effects on the wall. However, the dependence of viscosity on the temperature, on the geometric configuration of the resistors, and most important of all, on the end effects all tend to create distortion of the basic linear characteristic. Since linear resistors are very desirable in fluidic circuits, it would be most useful to investigate the various governing criteria of flow through small cylindrical and rectangular ducts.

Recent work published in NRC indicated the nonlinear effects on flow through small ducts with rectangular cross-section when compressibility, inertial and frictional effects are all taken into consideration. Students intending to carry out this topic as their research project should consider the following aspects:

(a) critical review of the existing literature regarding this subject which should be very well documented;

(b) develop a theoretical model of laminar flow through narrow fluid passages by taking into consideration all the significant parameters;

(c) experimentally measure the pressure drop and flow rate relationship across a series of linear resistor configurations

in an attempt to establish a meaningful governing parameter for fluid flow of this nature;

(d) tabulation of data in the form of a handbook for ease of future fluidic resistor design.

FLUIDIC CAPACITORS

Fluidic capacitors are used in both analogue and digital fluidic systems in a manner similar to their electrical counterparts. The fluidic capacitor consists of a volume of appropriate size with one or more input-output ports. Such a volume invariably represents a capacitance connected to ground on one side, since the capacitance effect basically arises out of the compressibility of fluid within the volume with the atmosphere as reference. Fluidic capacitance also has strong dependence on the pressure level as well as on the ratio of specific heats of the fluid. At the present time, the fluidic circuit designers are faced with two problems:

(a) exact design procedure for capacitors of specific values;

(b) design of fluidic capacitors which can be considered as an exact analogue to a true series electrical capacitance.

The aforementioned problems indicate the need for a thorough analytical and experimental study on the subject of fluidic capacitance. A research project in this area should preferably include the following:

(a) development of an analytical model on the charging and discharging phenomenon of the fluidic capacitor;

(b) investigation of the interrelated effects of the pressure level, ratio of specific heats (i.e. isothermal or adiabatic or some specific values) and the frequency of operation;

(c) tabulation of experimental data for use in the analytically derived equations for simplification of fluidic capacitor design.

VORTEX INDUCTION PUMP

It seems feasible to operate fluidic amplifiers under vacuum and using atmospheric air as the power supply. Since atmospheric pressure will remain reasonably constant, choke nozzle principle may be utilized as flow regulator for the system. There is another important implication of this approach. Since the atmospheric air is relatively free from oil, the possibility of experiencing oil contamination may be minimized.

In order to create adequate vacuum for the system, efficient induction pumps should be investigated. Normal induction pumps have very low efficiencies (limited to approximately 30%). However, it is possible to improve the efficiency by designing an induction pump with a swirl-inducing chamber. The formation of strong vortex flow by the primary jet will induce additional vacuum and could significantly improve the maximum efficiency obtainable by conventional techniques. It should be noted that such a pump will have no moving parts, and tremendous potential for many industrial applications can be realized.

LAMINAR JET PROPORTIONAL AMPLIFIER

In the area of analogue fluidics there exists a need for the development of a low noise, high gain proportional amplifier. Such an amplifier could be realized by employing a laminar flow power jet in a beam deflection type amplifier. However, the stability of a laminar jet is greatly influenced by the presence of control flows and by the device geometry, and further theoretical and practical work is necessary.

Proposed research in this area would include:

(1) Investigation of laminar jet stability in the presence of a control pressure field.

(2) Research into the geometric parameters required to attain a laminar jet deflection proportional amplifier.

(3) Consideration of the amplifier dynamic range as limited by the output pressure fluctuations induced by laminar jet instability modes.

(4) The study would be an extension of the NRC turbulence amplifier dynamic response investigations and would of necessity involve the fabrication of practical prototype devices in order to realistically simulate ambient disturbance conditions when evaluating laminar jet stability.

TURBULENCE AMPLIFIER CAVITY OPTIMIZATION

The transition or switching time from laminar to turbulent states, and vice versa, in a turbulence amplifier have been observed to be unequal. The turbulent to laminar reverse transition generally takes a longer time due to the presence of residual turbulence within the amplifier cavity. This phenomenon is the major cause of malfunctions in practical industrial circuits using turbulence amplifiers, and therefore merits an investigation oriented towards the design of these devices to achieve equal forward and reverse switching times.

A project in this topic would probably involve:

(1) Analysis of the power jet cavity effects on the amplifier dynamic performance to establish design criteria for the minimization of the reverse transition time delay, while retaining the laminar jet stabilizing effect of the confining cavity.

(2) Use of water tunnel flow visualization with subsequent real size prototype dynamic response evaluation.

LAMINAR JET STUDIES

Analytical studies on laminar jets, in general, could be useful in the design of fluidic devices incorporating such jets. For example, a three-dimensional analytical solution for the velocity distribution in the laminar jet of a turbulence amplifier may prove useful in the prediction of the signal transport times and of the dynamic response.

A typical problem could consist of a theoretical analysis of three-dimensional velocity distribution in the mixing zone between an initially uniform velocity laminar jet and ambient, and between an initially parabolic velocity profile laminar jet and ambient. Analytical solutions exist for two-dimensional velocity distributions of mixing laminar streams. (ref.: Schlichting "Boundary Layer Theory", p. 175).

II. HYBRID FLUIDICS

- HYBRID FLUIDIC PULSE SHORTENER
- FREE DISC DEVICES
- FLUIDIC SIGNAL GENERATOR
- BILATERAL ELECTRIC/FLUIDIC TRANSDUCER

HYBRID FLUIDIC PULSE SHORTENER

In many fluidic logic control circuits, there exists the requirement for pulse shorteners or special devices capable of producing short output pulses of precise duration when supplied with step input pulses. At present, this special function is performed by using two 2-input monostable fluidic amplifiers with suitable delay lines. However, a much simpler device may be developed using the magnetic/free disc principle as shown in Fig. II-1.

When a step input is applied, the metal disc will separate from the magnet and travel towards the output port, thereby generating a compression pulse. When the step input signal turns off, the disc will return to the input port.

The major problem involves analytical study of the dynamic behaviour of the disc under the action of the magnetic force as well as the pressure force. Simple experimental investigation should be carried out to study the output waveform in order to further substantiate the theoretical analysis. Results should provide important interrelationship of various geometric parameters and optimization of design procedure.

FREE DISC DEVICES

Pure fluidic technology undoubtedly offers many advantages because of its reliability and capability to withstand extreme environmental tolerances. However, in many applications, the requirement for reliable operation under extreme conditions is not necessarily the most important governing factor. Consequently, it may be advantageous to apply fluidic devices in conjunction with some form of moving parts in applications where absolute reliability is not the important criterion. This may first appear to be a retrogressive step; however, industrial applications do not necessarily require the full potential offered by pure fluidic devices regarding life and extreme environmental tolerances. In most cases, economics becomes the governing parameter in selecting the appropriate scheme whether it is fluidic, mechanical or electronic. Therefore, any system capable of performing the required functions and offering the best economical advantages will be preferred.

Two problem areas which hinder the full utilization of fluidic devides are the high power consumption and the detrimental effects of air contamination. There is also an urgent requirement for very high input impedance amplifiers. A simple, free-disc concept was conceived and found to work easily in conjunction with existing fluidic devices. The basic operational principles of these free-disc passive devices are shown in Figs. II-2, -3 and -4. Furthermore, by coupling these simple disc valves with the type of bistable amplifiers

previously described, it is possible to achieve a simple binary counter function.

It is apparent that, in order to achieve optimum design of these free-disc devices, additional effort to theoretically analyze the free-disc movement within a thin cylindrical chamber is desirable. Furthermore, an analytical model relating all the physical parameters of this disc and chamber configurations will be most useful in the development of these devices into practical hardware.

FLUIDIC SIGNAL GENERATOR

The problem concerns the design of a device that will convert an electrical signal (i.e. sine, square or triangular) into an identically shaped undistorted pressure signal. The desired frequency range is in the neighbourhood of 0 to 2 KHz with peak-to-peak signal amplitudes varying from 0.1 to 3.0 psid. A device of this type will be most useful for frequency response tests on fluidic elements and systems. It could also be used as an interface from an electrical to fluidic system.

Briefly, such a device may consist of an electro-mechanical actuator element coupled to an air flow modulator which can be a flapper nozzle. Preliminary work done at SGWU in this area resulted in the development of two single-ended generators and one push-pull signal generator, based on the moving coil-flapper nozzle combination. Two of these respond well up to 600 Hz, and one produces a signal over a range from 0 to 1 KHz with peak-to-peak signal pressure levels up to 1 psid.

BILATERAL ELECTRIC/FLUIDIC TRANSDUCER

From simple electromagnetic transduction principles, it appears technically feasible to design a unique device which transforms signals from electric to fluidic and vice versa, thus performing a bilateral transducer function. The preliminary design concept and various operational modes are shown schematically in Figs. II-5a and -5b.

Basically, the device would consist of a cylindrical chamber through which pneumatic flow takes place. The chamber also houses a cylindrical bar magnet. It should be noted that the input and output ports are designed slightly differently so that the flow is completely shut off when the magnet is closed against the fluidic input end of the chamber; however, a controlled amount of flow is allowed to leak through the device when the magnet is closed against the seats of the output port. Two solenoid coils are wound around the outside of the chamber; these are used to drive the magnet when they are electrically energized. The magnet may thus be displaced by pneumatic pressure, magnetic force, or by a balance force between them.

III- SYSTEMS

- HEADING REFERENCE
- FLUIDIC STATISTICAL COMPUTATION
- FLUIDIC DIGITAL TO ANALOGUE CONVERSION TECHNIQUE
- FLUIDIC ANALOGUE TO FREQUENCY CONVERSION TECHNIQUE
- PULSE WIDTH MODULATION
- MEDICAL FLUIDICS (RESPIRATOR)

HYBRID FLUIDIC HEADING REFERENCE

A closed loop feedback heading reference system using a fluidic vortex rate sensor has been conveived as shown in Fig. III-1. The feedback loop around the fluidic rate sensor is intended to maintain the sensor at a fixed orientation about the rotational axis in the presence of rotation of the sensor support frame. The major problem involved in this system is the possibility of instability due to pure time delay associated with the fluidic vortex rate sensor.

By means of analogue simulation, some alternate time delay compensation scheme can be realized. It appears practicable that the performance of such a system can be optimized. In addition, the following problem areas should be considered:

(a) improvement of the fluidic vortex rate sensor performance by carrying out a critical parametric study of the device;

(b) consideration of means to replace the present pneumatic pick-off arrangement by means of an electrical pick-off element for the fluidic vortex rate sensor;

(c) investigation of feedback compensation techniques to improve the time response of the system.

FLUIDIC STATISTICAL COMPUTATION

With presently available information on digital computational techniques, it is possible to utilize the simple fluidic logic elements to perform relatively complex mathematical computation. In general, fluidic amplifiers are simple, efficient, binary gates and as such fit easily into statistical computation schemes. For example, a certain function F(x) can be represented by a fluidic pulse width modulated signal, and dx can be realized by simple pulse shorteners. The two signal trains can be summed together by means of a simple fluidic binary "AND" gate. The output of the "AND" gate, based on statistical theory, represents the product of the form [F(x).dx].

This is a most interesting project which at the same time also provides excellent potential for practical applications. Students can undertake the project to improve the accuracy of computation and devise methods for practical implementation of such techniques.

FLUIDIC DIGITAL TO ANALOGUE CONVERSION TECHNIQUE

At present, most of the fluidic logic circuits are engineered digitally mainly because of the accuracy required and the availability of better digital amplifiers. It is, however, generally desirable to have the final output signal converted back into analogue form for practical applications. Special devices or techniques of this nature are particularly important in converting digital signals in binary form to analogue pressure signals.

Among all the various approaches, the most simple and promising one is shown schematically in Fig. III-2. The circuit is a simple D/A converter with four bit resolution. It consists of three proportional amplifiers and four "binary-weighted" resistors. The beauty of this approach is the fact that resistors need not be linear because the input signal will be digital and therefore of a fixed magnitude. By tracing the operation of the circuit with different combination of input conditions, it can be easily seen that the final output pressure level will be proportional to the binary signal strength. D/A converters of this type have been successfully breadboarded and have shown linearity of the order of $\pm$ 1.0% with a resolution of 15:1.

Further investigation in this topic should be carried out to include the following:

(a) systematic analysis of the circuit operation and possible improvement of system resolution;

(b) investigating means to minimize noise in the proportional amplifiers because the limitation of the system resolution is dependent directly on the amplifier noise level;

(c) development of methods for selecting the appropriately weighted resistors;

(d) evaluation of the overall system response and establishment of the amplifier frequency response requirement.

FLUIDIC ANALOGUE TO FREQUENCY CONVERSION TECHNIQUE

In most logic systems, there exists the requirement of converting an analogue pressure signal (e.g. output from a fluidic back pressure sensor) into a frequency modulated signal. Many approaches have been tried in an attempt to achieve two major objectives: good linearity and large frequency range.

One simple scheme utilizing two commercially available fluid elements have been breadboarded and shown to provide most encouraging results on frequency vs. analogue input signal characteristics. The circuit schematic is shown in Fig. III-3a. Students who are interested in this topic and contemplate selecting it as the research project should consider the following:

(a) acquire better understanding of the actual operating mechanism of this scheme. Basically, this relates to the variation in amplifier switching time vs. supply pressure;

(b) development of a simple mathematical model to predict performance and linearity of the system;

(c) breadboard two such similar circuits and connect them in push-pull configuration to a proportional input element (see Fig. III-3b);

(d) investigate other methods of increasing the input impedance of the converter.

PULSE WIDTH MODULATION

In most practical fluidic circuits, it is generally necessary to convert the analogue pressure signal into a pulse width modulated signal. One possible scheme is illustrated in block diagram form in Fig. III-4. This can be achieved by algebraically subtracting triangular pressure pulses from the analogue pressure signal in a proportional amplifier and using the differential output pressure of the proportional to switch the bistable amplifier. Triangular pulses can be obtained by feeding an oscillator output into a fluidic R-C combination. Resolution in the neighbourhood of 20:1 has been obtained in the preliminary breadboarded circuit. Further studies should be carried out in the following areas:

(a) reduction in noise of proportional amplifiers to improve resolution;

(b) devise methods to obtain clean triangular waveform and technique for selecting appropriate capacitance values;

(c) improve the consistency of bistable element switching by using higher gain proportional amplifiers.

MEDICAL FLUIDICS (RESPIRATOR)

Fluidics, because of its simplicity and reliability, appears to be ideally suited for medical applications. For example, a fluidic heart pump has been built and successfully tested. It is believed that the advantages of fluidics can be further explored if it is implemented in the design of a respirator. Basically, a respirator can either function as a device assisting patients who need support in breathing, or as a controller in the absence of rhythmic respiration. The simple switching characteristics of the power jet in the fluid amplifier can be made to provide synchronized operation of the respirator with the breathing rate of the patient.

There are two basic types of respirator, one pressure limited and the other volume limited. Both of these can be developed using simple fluidic logic elements. An instrument of this nature properly developed will offer great assistance to people in the medical field. Students interested in this type of project should first have taken the course E651 (Fluidics) and also obtain all the related medical information on respirators.

APPENDIX F

FLUIDICS RESEARCH GROUP - INTERNAL REPORTS

A Variable Sine Function Generator for Fluidic Frequency-Response Studies, John C. Vrana, May 1968. (Progress Report).

A Variable Sine Function Generator for Fluidic Frequency-Response Studies, John C. Vrana, June 1968. (Progress Report).

A Variable Sine Function Generator for Fluidic Frequency-Response Studies, N. Suresh and J.C. Vrana, July and August 1968 (Progress Report).

Turbulence Measurements in the Velocity Field of a Three-Dimensional Air Jet by Constant-Temperature Hot-Wire Anemometer, S. Tsang, August 1968.

Turbulence Research - Signal Generation and Transmission, H. Azria, R. Kahawita and N. Suresh, November 1968.

Preliminary Results from Turbulent Jet, H. Azria, N. Suresh and R. Kahawita, January 1969.

An Experimental Study of the Turbulence Characteristics in a Three-Dimensional Incompressible Free Jet, H. Azria, N. Suresh and R. Kahawita, June 1969.

PATENT DISCLOSURE FOR A PRESSURE SIGNAL GENERATOR

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St. Bruno, Que.

Assigned to: Department of Mechanical Engineering,
Sir George Williams University,
Montreal.

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25th July, 1968

Figures 1 and 2 appended illustrate two embodiments of the invention. It is the object of the Pressure Signal Generator to produce clearly defined test signals for fluidic system and transmission line research using air. A sine-wave of any desired frequency is one such test signal required. The subject invention is an electro-pneumatic transducer with a flat frequency response and very little distortion. It can consequently provide a pressure signal of the same form as is input to its electrical terminals, subject to distortion from alteration of harmonics above an upper frequency limit of the order of 1 KHz.

The pneumatic power is supplied via the air inlet(s) (1), whence the air flows through porous restrictor(s) (2) into the sensing chamber(s) (3). The area of the annular orifice(s) (4) is variable by the displacement of flapper (5) under the action of electromagnetic forces from the voice coil(s) (6), which are immersed in the magnetic field of magnet(s) (7). Variation of this area results in a corresponding variation of the pressure in the sensing chamber (3), giving rise to the desired signal.

Features claimed for the subject Pressure Signal Generator are:

1. Low distortion, arising from the cancellation of the non-linearity of a half-bridge circuit with one leg variable with the non-linearity of the air flow restrictor, as shown in Fig. 3.
2. Low noise in the range of interest due to smooth flow through all components.
3. Flat frequency response to beyond the resonant frequency of the flapper due to features of the pneumatic stiffness interacting with mechanical and electrical damping.
4. Ability to drive fluidic loads of up to 1/4 of the pneumatic input admittance with low distortion.
5. Further reduction of distortion by the inclusion of the Pressure Signal Generator in the feedback loop, through a pressure pick-up in close proximity and connecting with the sensing chamber. An example of such an arrangement is shown in Fig. 4.

For the arrangement of Fig.2, additional features claimed are:

6. Symmetrical push-pull output.
7. Ability to adjust damping by shunting one coil.
8. Independent control of mean signal pressure ($\overline{P}_3$) and of alternating signal pressure (p_3).
9. A simple, matched impedance termination for the signal line and a simple construction for the restrictor and sensing chamber.

Date: July 25, 1968 Signed: J. E. Vl[illegible]

WITNESSED AND UNDERSTOOD BY: [illegible]

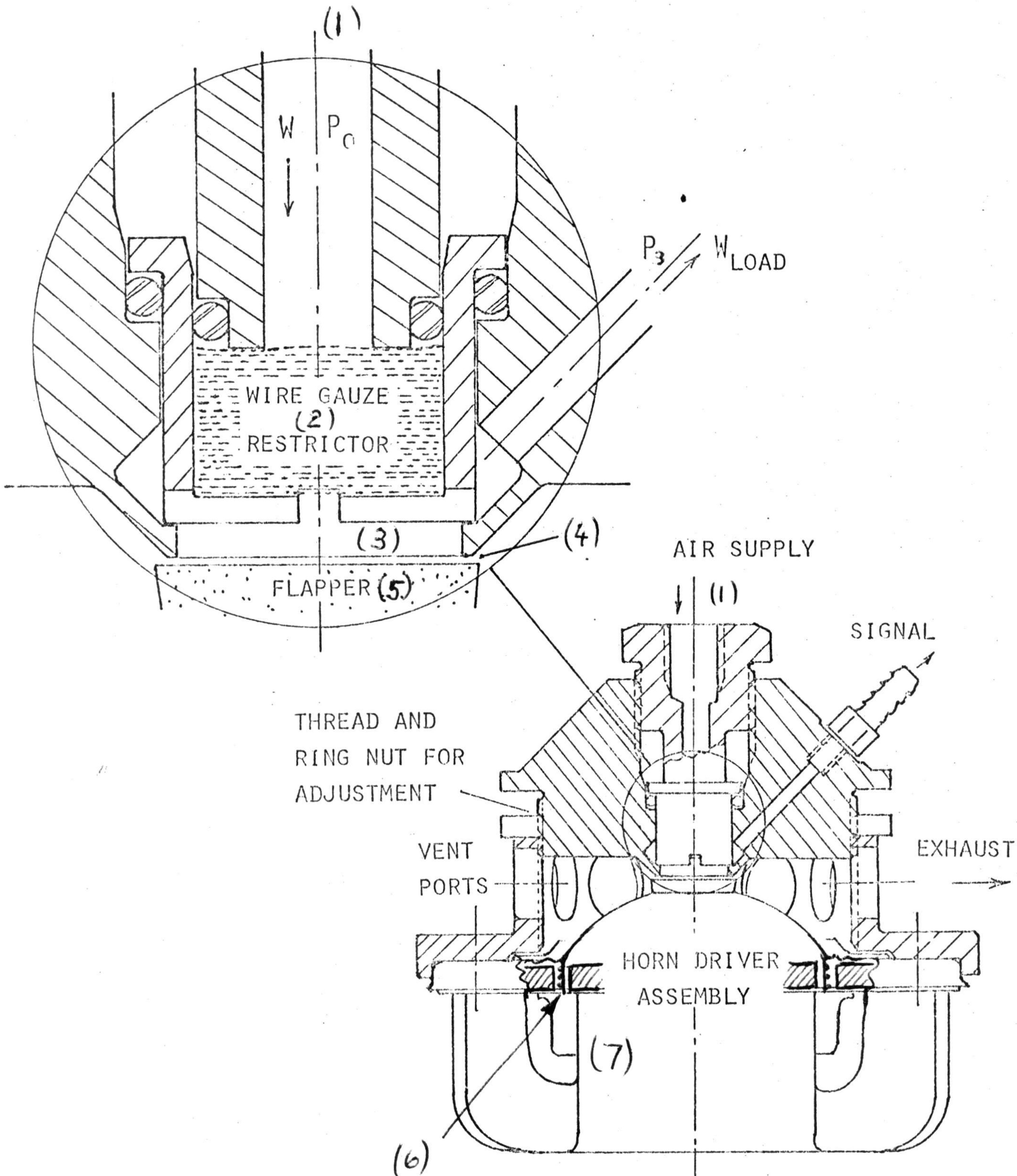

FIGURE 1

CROSS-SECTION OF THE SIGNAL GENERATOR

J.C.W.
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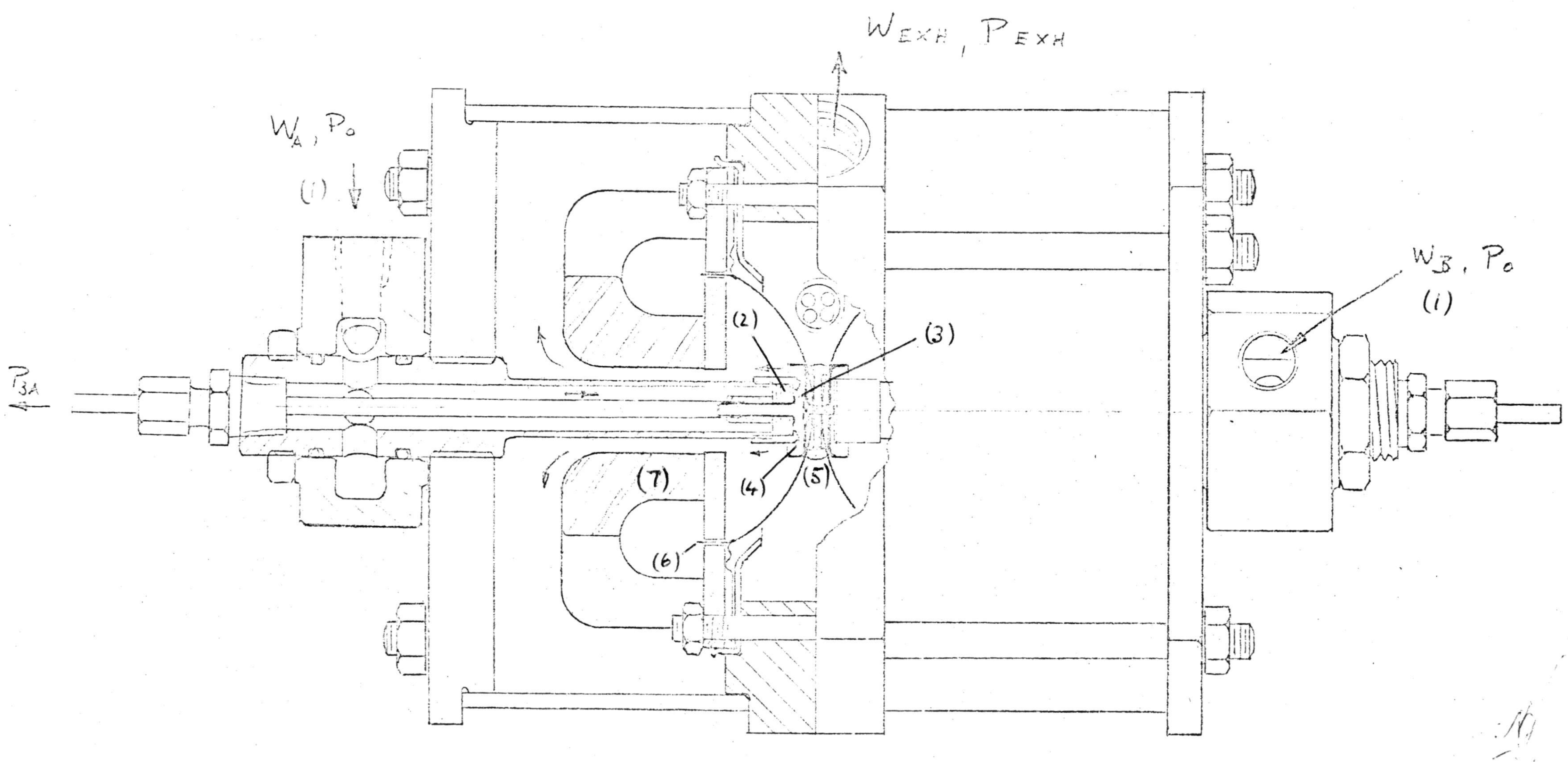

FIGURE 2

PUSH - PULL PRESSURE SIGNAL GENERATOR

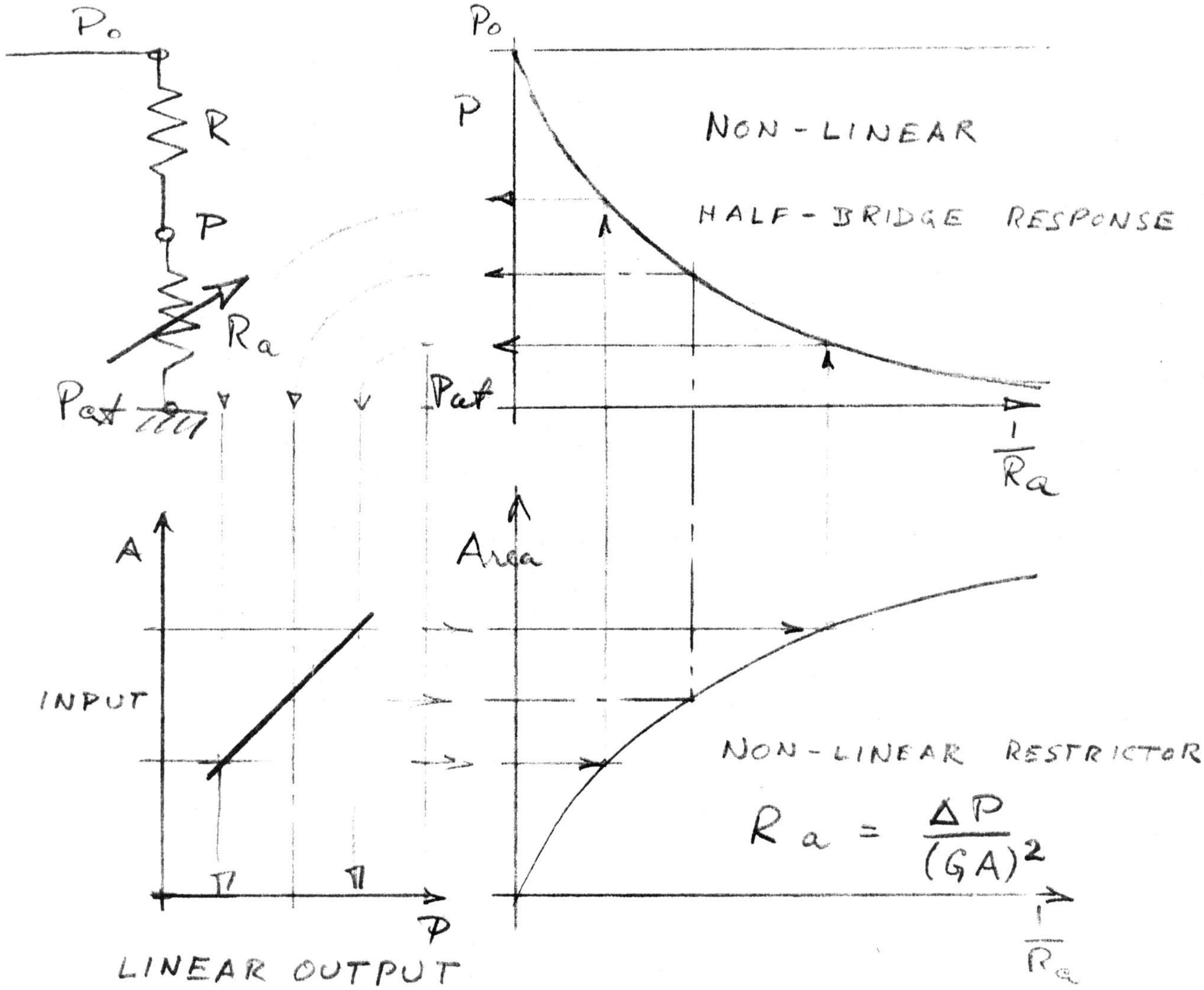

FIG. 3

CANCELLATION OF NON-LINEARITIES

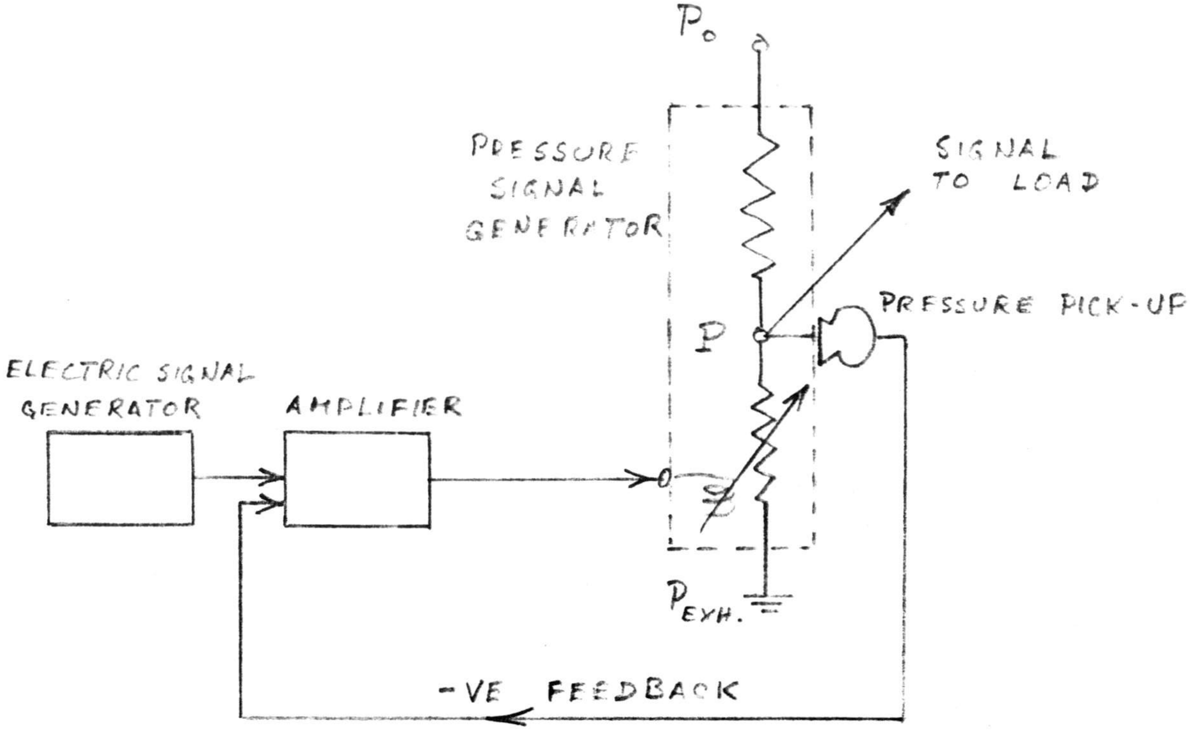

FIG. 4

IMPROVEMENT IN FIDELITY THROUGH FEEDBACK